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Two Derivations Suffice: the Role of Syllabification in Cognitive Phonology

Technical Report AIP - 116

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Abstract

This report contains three papers from an ongoing research project on connectionist phonology. The first introduces syllabification into our "many maps" processing model. The second shows how syllabification and a previously-described clustering mechanism can be used jointly to implement the stress assignment rules of a number of languages. The third paper describes a preliminary version of a phonological rule-learning program whose rule syntax is determined by the architecture of our model.

Earlier work in connectionist phonology is described in reports CMU-CS-89-144: "A Connectionist Implementation of Cognitive Phonology," CMU-CS-89-158: "Rules and Maps in Connectionist Symbol Processing," and CMU-CS-90-112: "Rules and Maps II: Recent Progress in Connectionist Symbol Processing."

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1 Introduction

Following a suggestion of John Goldsmith, first published as (Goldsmith 1990), George Lakoff's theory of "cognitive phonology" (Lakoff 1988, 1989) strives to eliminate both ordering constraints and sequential application of rules. We are developing a *connectionist interpretation* of cognitive phonology, and in the process, revising Goldsmith and Lakoff's original proposals in significant ways. Recently we added a syllabifier to our model. In this paper we show how syllabification provides the motivation for epenthesis and deletion processes, which consequently don't need to be stated as independent rules in most cases, thus limiting the depth of derivations. We hypothesize, based on this and previous work, that "two levels of derivation" is a computational constraint that can be met by all human languages.

Lakoff uses data from Mohawk, one of the five Northern Iroquoian languages, to introduce the fundamental principles of his theory. In standard theories of generative phonology, derivations consist of long sequences of rule applications with numerous intermediate steps. Mohawk seems to offer an extreme case of this, and Lakoff (1989:4) gives the following derivation to illustrate a case where six rules, extrinsically ordered to a depth of four, apply to a form /ye-ʌ̃-k-hrek-?/ "I will push it (away)" taken from Halle and Clements (1983):[1]

/y e ʌ̃ k h r e k ? /	
y ʌ̃ k h r e k ?	*by vowel deletion*
y ʌ̃́ k h r e k ?	*by stress assignment*
y ɔ́ k h r e k ?	*by vowel change*
y ɔ́ k h r e k e ?	*by epenthesis*
y ɔ́ k h r e g e ?	*by voicing*
y ɔ́ k r e g e ?	*by h-deletion*
[y ɔ́ k r e g e ?]	

Lakoff's cognitive phonology theory—and our revision of it—is an attempt to come to terms with the fact that such long derivations, with numerous intermediate steps, are not psychologically or biologically plausible. Cognitive phonology offers an alternative; one which is in principle consistent with connectionist models. In this theory there are three distinct levels of representation:

[1] It is not entirely clear whether there is a vowel present in the underlying representation of the translocative prefix /ye-/. Marianne Mithun, a specialist in Iroquoian languages, suggests that the same /e/ "occurs as an increment with most other outer prepronominal prefixes when they appear immediately before pronouns."

the morphemic (M), the phonemic (P), and the phonetic (F).[2] Phonological processes expressed as rules in standard theories are instead treated as "constructions" of two types:

- Cross-level M-P and P-F constructions, which state allowable correlations between levels.
- Intra-level P and F constructions, which state well-formedness constraints within a level.

There is no extrinsic rule ordering in Lakoff's theory; all constructions at a given level apply simultaneously. However, by allowing both cross-level and intra-level constructions, Lakoff is able to simulate the effect of an extrinsic rule ordering up to a depth of four, as appears to be needed in Mohawk.[3] In his theory, there are essentially four distinct sets of constructions, and the apparent ordering follows from the interaction of the components.

Vowel deletion:	M-P construction
Stress:	P level constraint
Epenthesis:	P-F construction
Voicing:	F level constraint

Lakoff's derivation of the Mohawk form "I will push it away" is shown below. Further details of his analysis follow in the next section.

M:	y e + ʌ̃ + k + h r e k + ?	
	| |	*vowel deletion (M-P)*
P:	y ʌ̃́ k h r e k ?	*stress (P)*
	| | |	*epenthesis (P-F)*
F:	y ɔ̃́ k r e g e ?	*voicing (F)*

Recently we argued, on both computational and theoretical grounds, that cognitive phonology should utilize only cross-level constraints (Wheeler & Touretzky 1989; Touretzky & Wheeler 1990). Our connectionist implementation of cognitive phonology still uses three levels of representation, and therefore has just two derivational steps: M-to-P and P-to-F. In order to regain some of the computational power lost by eliminating intra-level rules, we have introduced two bits of non-derivational machinery which impose some structure on the M-level and P-level representations. The first bit was a "clustering" mechanism, described in the references cited above, for handling iterative phenomena such as harmony. The second bit, syllabification, is the subject of this paper.

We begin by examining Lakoff's Mohawk solution in more detail, to see why it depends on intra-level constraints. Next we give an overview of our implementation, called the "many maps" model, and show how M-P and P-F mapping rules are implemented in a connectionist network. We then broaden our discussion of Mohawk to include additional processes, which result in further complexities. Finally we explain the role of syllabification in our version of cognitive phonology. Adding a syllabification component to our mapping circuitry allows us to correctly model the Mohawk data using only two derivational steps, with no intra-level constraints.

[2] Goldsmith refers to these levels as M, W, and P, respectively.

[3] There are two rules in the Halle and Clements /yeʌ̃khrek?/ derivation that are suspect. According to Mithun, there is in fact no h-deletion here at all: "the h comes through phonetically very loud and clear, though someone who is used to aspirated stops in English could fail to notice it." As for the /ʌ̃/ vowel, which is something close to the vowel in the English word "junk", Mithun says that in situations like this where it occurs in a closed syllable, the nasalization tends to disappear but the quality of the vowel is certainly far from [ɔ].

2 Lakoff's Cognitive Phonology Analysis

In this section we describe the rules—and ordering relations between rules—in Lakoff's Mohawk example. Lakoff (1989) based his analysis on data taken from Halle and Clements (1983), and there is reason to believe that there may be some inaccuracies in the data presented there (Marianne Mithun, personal communication). We wish to be as honest to the data as possible, and so, to avoid perpetuating inaccuracies, we have taken the liberty of modifying Lakoff's constructions in this paper—without violating the spirit of his analysis—to fit the corrected data.

Lakoff's (1989:4) vowel deletion rule, which deletes a vowel before another vowel in "I will push it away," must be ordered before stress assignment, because "When an underlying sequence 'VC_0VVC_0#' occurs, the second vowel deletes and the first vowel is stressed."

There is a slight problem here. The data we have shows that the vowel deletion process in /ye-ʌ̃-k-hrek-ʔ/, if in fact it is a rule of the grammar at all (see footnote 1), is not the same process operating in the schematic case Lakoff bases his ordering argument on. In /ye-ʌ̃-k-hrek-ʔ/ the *first* of two vowels deletes, but in many cases of the form VC_0VVC_0# it is the *second* vowel that deletes.[4] Consider the following examples provided by Mithun:

/hro-awʌ̃/ → [ró:wʌ̃] "it is his"

/hro-ahtũ/ → [róhdũ] "he has disappeared"

The vowel deletion rule for these cases is formalized as:

$$\text{Vowel deletion:}\quad \begin{array}{lcc} \text{M:} & V & V \\ & & | \\ \text{P:} & & \emptyset \end{array}$$

In any case, the argument still stands that vowel deletion must precede stress assignment. If stress were to apply first in a form like /hro-ahtũ/ then stress would be incorrectly assigned to the penultimate underlying vowel /a/, the vowel that ultimately deletes. Lakoff's stress rule is shown below.

$$\text{Stress:}\quad \text{P:}\quad X\,C_0\,V\,C_0\,\#\,;\ \textit{If}\ X = V\ \textit{then}\ X = [+\text{stress}]$$

The remaining rules of concern to us here are epenthesis and voicing. In standard generative analyses, epenthesis must precede voicing, since the application of epenthesis creates the environment for voicing. In Lakoff's analysis epenthesis is stated as a P-F construction, with intervocalic voicing being an intra-level rule applying at F-level. In this way he is able to account for the feeding relation between those rules without having to stipulate an extrinsic ordering or assume serial rule application.

$$\text{Epenthesis:}\quad \begin{array}{lcccc} \text{P:} & [\,] & & [\,] & \# \\ & | & | & | & \\ \text{F:} & C & e & ʔ & \end{array}$$

The voicing rule is actually presonorant voicing according to Mithun, and we have stated it this way below.

---

[4]The conditions on vowel deletion appear to be remarkably complex, and may depend on the qualities of the vowels. We refer the reader to (Hopkins 1987) for a discussion of the problem and an interesting proposal.

Voicing: F: X [+son] ; *If* X = [−son] *then* X = [+voice]

One thing to notice here is that the voicing rule *must* be stated as an F-level constraint in Lakoff's analysis, not a cross-level construction applying between P and F, because the epenthetic vowel is not present at P-level. Thus it could not trigger a rule whose environment was stated at P.

The epenthesis rule must be ordered after stress assignment, since epenthetic vowels do not enter into stress assignment. In a traditional analysis this would be accounted for by extrinsically ordering the rules so that stress assignment precedes epenthesis. Lakoff achieves this same goal by having epenthesis be a P-F construction while stress applies at P.

Regardless of the differences between Lakoff's original rules and our restatement of them, there is clearly an ordering relation between at least four rules in Mohawk. The following forms show the interactions of these four constructions. Consider, first, [róhdũ] "he has disappeared". We assume here that the initial /h/ of the prefix /hro-/ ("masculine patient") is deleted by a cross-level P-F construction, though nothing hinges on this assumption.

M:	h r o + a h t ũ	
	|	*vowel deletion (M-P)*
P:	h r ó h t ũ	*stress (P)*
	|	*initial h-deletion (P-F)*
F:	r ó h d ũ	*voicing (F)*

The important thing to notice here is that by stating vowel deletion as an M-P construction, the relation between vowel deletion and stress assignment is accounted for, since stress is analyzed as a P-level rule and the vowel is not present at that level, having been deleted by the M-P construction. Furthermore, the derivation of "I will push it" below clearly shows the interaction of stress and epenthesis. Here again we get the correct predictions because stress is applied at P-level, and the epenthetic vowel appears only at F-level. Stress could be stated as a P-F rule and nothing would go awry, but other things being equal, Lakoff prefers intra-level rules to cross-level rules (Lakoff 1989:4). This is one of the weaknesses of his theory: it is underconstrained.

M:	ʌ̃ + k + h r e k + ?	
P:	ʌ̃́ k h r e k ?	*stress (P)*
	|	*epenthesis (P-F)*
F:	ʌ̃́ k h r e g e ?	*voicing (F)*

Ultimately, the epenthetic vowel that shows up at F-level feeds the voicing process, which Lakoff describes as an F-level well-formedness constraint. Because of the interaction with epenthesis, voicing *must* be an intra-level rule. Thus, no matter how one tries to reanalyze the rules, a minimum of three distinct rule components are needed.

3 The "Many Maps" Model

Goldsmith's vision of how constraints might be implemented in a connectionist network draws support from Smolensky's "harmony theory," a neural network architecture based on statistical

mechanics and simulated annealing (Smolensky 1986). In (Wheeler and Touretzky 1989; Touretzky and Wheeler 1990) we argue against appeals to harmony theory, first, because it does not appear feasible to express phonological constraints as terms in an energy function, as harmony requires, and second, because simulated annealing requires a large number of state updates to reach equilibrium, which violates the psychological and biological constraints that were the original motivation for this work.

Our attempt to implement the theory in a connectionist network led us to revise it to eliminate intra-level constraints. In this section we show how our "many maps" model implements cross-level constraints, and in following sections explain how the addition of syllabification allows us to explain the Mohawk data using only two rule components rather than Lakoff's four.

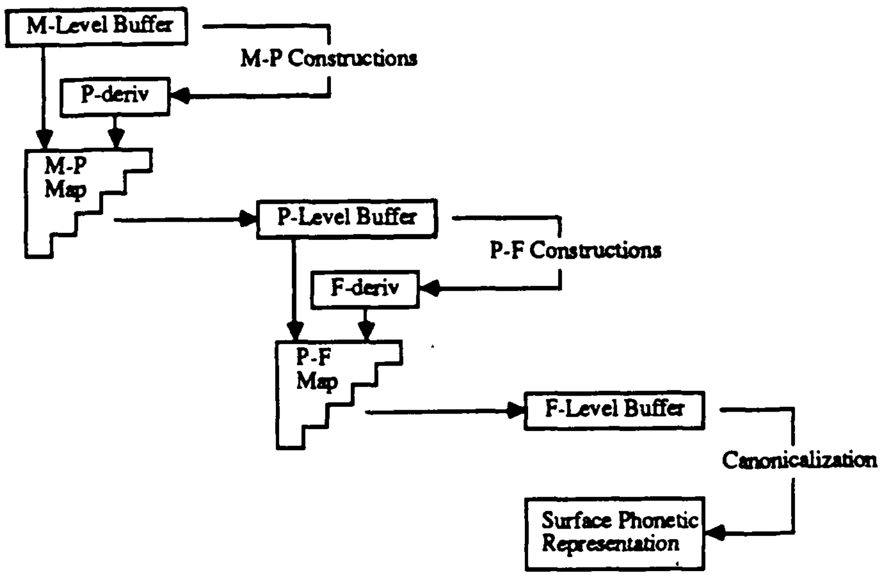

Figure 1: Overview of the "many maps" model.

The input to our model (see Figure 1) is the M-level representation of an utterance. M-P constructions control a mapping matrix, first described in (Touretzky 1989), that derives the P-level representation. P-F constructions control a second, identical matrix that derives the F-level representation. Each mapping matrix can perform an arbitrary number of string update operations (mutations, insertions, and deletions) in parallel. A final "canonicalization" step fills in missing features of underspecified segments; it will not be discussed further in this paper.

The inputs to a mapping matrix are a segmental buffer and a change buffer, called a "deriv" buffer, that describes how the input sequence should be changed to derive the next level of representation. Since the deriv buffer makes provision for mutation, deletion, and insertion of segments, it defines a sort of grammar of phonological processes. Unlike previous connectionist phonology models, such as the Rumelhart & McClelland (1986) verb learning model, where the "rules" (actually weights) manipulate phoneme sequences directly, in our model the rules are constrained to operate within the deriv buffer's grammar. Thus, our model cannot implement a large class of impossible phonological

rules, such as "reverse all the segments in the utterance," which direct-manipulation models have no trouble implementing.

In eliminating intra-level constructions such as the F-level presonorant voicing rule, we are faced with an obvious problem: how to account for the complex interactions between rules in Lakoff's Mohawk example. Without intra-level constructions, if epenthesis is stated as a P-F rule, as in Lakoff's account, then we have run out of levels below and have no way of accounting for presonorant voicing. We believe that presonorant voicing should be a P-F construction, stated as follows: [5]

Preson. voicing:	P:	[−son]	[+son]
		|	
	F:	[+voice]	

But, because of the interaction with epenthesis (the epenthetic vowel may trigger voicing), this forces epenthesis to be an M-P construction. Here again, we are apparently in trouble because we have run out of levels above. Stress must precede epenthesis, and vowel deletion must precede stress. Syllabification will provide a solution.

We conclude this section by illustrating the operation of the mapping matrices in more detail. The P-F mapping matrix is shown in Figure 2. Several P-F rules are being applied to the P-level representation of the Mohawk word /k-ahsi?t-a?-ke/ "(on) my foot" to derive the surface form [gahši?dà:ge]. Due to space limitations, only part of the word is shown in the figure, but the model actually processes the entire word simultaneously.

The leftmost instance of rule application in Figure 2 is a palatalization process that changes /s/ to /š/ when it appears between an /h/ and an /i/. This is shown by recording the mutation [+high] in F-deriv. Next is the presonorant voicing rule, discussed previously; it changes /t/ to [d]. A third process converts a stressed vowel followed by a tautosyllabic glottal stop to a long vowel with falling tone, deleting the glottal. This is indicated in P-deriv by a combination of mutations and a "1" in the deletion slot.

The rules themselves are not shown in Figure 2. Rules simply read the contents of the M- or P-level buffer and write their changes into P- or F-deriv, respectively.

4 Further Discussion of Mohawk

Before considering the role of syllabification in our model, we will formalize the new rules mentioned in the previous section and further broaden our coverage of Mohawk phonology to include a number of additional processes not treated by Lakoff.

First, palatalization applies to /s/ when it occurs between /h/ and either /y/ or /i/, with apparently some speaker variation. Palatalization before /y/ also occurs across /h/. For the moment we tentatively state the rules as follows, using the feature [+high] to indicate palatalization:

[5]Voicing in Mohawk is so automatic that it is not even encoded in the orthography, which leads to considerable confusion. Actually, there is a slight wrinkle here. The fricative /s/ is voiced initially before sonorants, but medially only between sonorants. We haven't incorporated this restriction in the rule.

Two Derivations Suffice

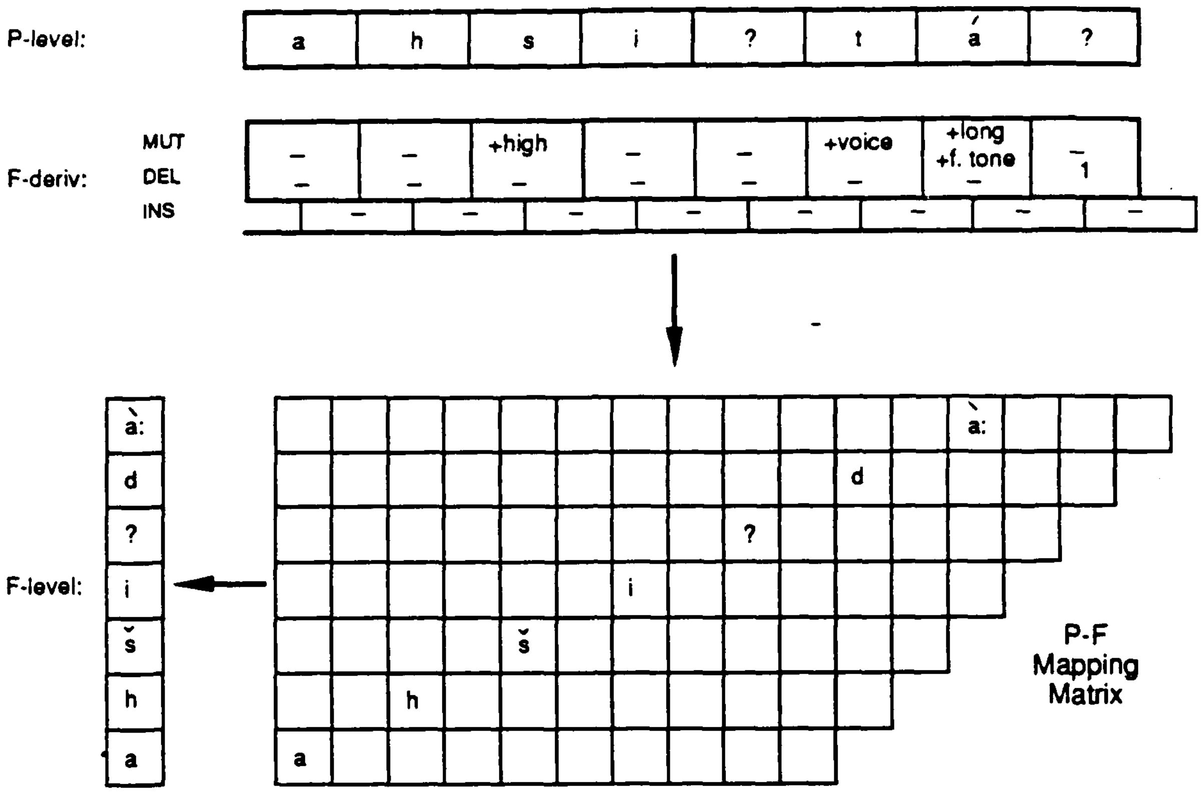

Figure 2: The mapping from P to F level.

```
P:   h      s      {i,y}
            |
F:      [+high]

P:        s      h   y          (cf. /s-hyatũ/ → [šyá:dũ] "write!")
          |      |
F:    [+high]    ∅
```

We have already discussed presonorant voicing, the other P-F process affecting consonants. We now consider P-F processes affecting vowels. One rule which comes into play in numerous derivations and is not discussed by Lakoff at all is a vowel lengthening process whereby a stressed vowel in an open syllable lengthens. Some examples follow; the first two are taken from Hopkins (1987:447):

/ku-at-awʌ̃-s/	→	[gudá:wʌ̃s]	"They (female) are swimming."
/hro-at-awʌ̃/	→	[rodá:wʌ̃]	"He swam."
/s-hyatũ/	→	[šyá:dũ]	"Write!"

Our P-F open syllable lengthening rule is formalized below:

$$\begin{array}{lll} \text{P:} & \acute{V} & \$ \\ & | & \\ \text{F:} & [+\text{long}] & \end{array}$$

As shown in the derivation for [gahši?dà:ge] "(on) my foot," there is a process by which a stressed vowel and tautosyllabic glottal stop followed by a consonant become a long vowel with falling tone.

$$\begin{array}{lllll} \text{P:} & \acute{V} & ? & \$ & C \\ & | & | & & \\ \text{F:} & \begin{bmatrix} +\text{long} \\ +\text{f. tone} \end{bmatrix} & \emptyset & & \end{array}$$

A related process converts a stressed vowel and tautosyllabic /h/ followed by a resonant in the next syllable into a long vowel with falling tone. For example, /i-hra-k-s/ "he eats" surfaces phonetically as [í:raks]. While the three lengthening processes might be collapsed in a standard generative notation, for maximum clarity we have not attempted to do so here, but instead state them as separate rules.

$$\begin{array}{lllll} \text{P:} & \acute{V} & h & \$ & [+\text{son},+\text{cons}] \\ & | & | & & \\ \text{F:} & \begin{bmatrix} +\text{long} \\ +\text{f. tone} \end{bmatrix} & \emptyset & & \end{array}$$

There is an additional epenthesis process in Mohawk, not discussed by Lakoff, that inserts /e/ between an obstruent and a following sonorant, as in the following examples:

/tnikʌ̃h/	→	[tení:gʌ̃h]	"You and I see it."
/swakʌ̃h/	→	[sewá:gʌ̃h]	"You all see it."
/wa?krʌ̃?/	→	[wà:gerʌ̃?]	"I filled it."
/ítwe?/	→	[í:dewe?]	"Let's (you all and I) go!"

Notice that in the third and fourth forms, stress assignment must apply prior to this form of epenthesis, which is formalized below as a P-F rule.

Obstruent-sonorant epenthesis:

$$\begin{array}{llll} \text{P:} & [-\text{son}] & & [+\text{son},-\text{syll}] \\ & | & | & | \\ \text{F:} & [\,] & e & [\,] \end{array}$$

Consider the derivation of the underlying form /i-tw-e-?/, which surfaces phonetically as [ídewe?]. An epenthetic /e/ has been inserted between the obstruent /t/ and the following sonorant /w/. Assuming that syllabification and stress assignment take place at M-P, the input to the P-F map will be /ítwe?/, in which the /t/ is tautosyllabic to the stressed /i/, forming a closed syllable. Hence, lengthening does not apply to the stressed vowel. If obstruent-sonorant epenthesis were an M-P process, the /t/ would not be a coda at P, and hence the conditions for P-F open syllable lengthening of the stressed vowel would be satisfied.

M:	i t w e ?	
	|	*stress assignment*
P:	í t w e ?	
	| |	*presonorant voicing; obstruent-sonorant epenthesis*
F:	í d e w e ?	

The process Lakoff cites that produces epenthetic /e/ occurs in our model as part of the M-P mapping, breaking up inadmissible consonant clusters, i.e., CCC or CC#. While the obstruent-sonorant epenthesis rule was sensitive to distinctive features of the segments, this rule is motivated by the need to establish well-formed syllable structures at P-level. We have no graphical notation for this rule because it is part of the syllabification mechanism to be explained in the next section, where we will also discuss the remaining M-P rules: vowel deletion and stress assignment.

5 The Role of Syllabification

Besides the original concern that our limited-depth derivational model will run out of levels unless further structuring mechanisms are added, we also want the model to reflect current understanding of the importance of syllable structure constraints in motivating epenthesis and deletion processes. This would remedy a weakness in Lakoff's version of the theory, namely, that it merely *describes* the epenthesis and deletion operations; it does not acknowledge the underlying motivating factors. Since Kahn (1976), the syllable has played an increasingly significant role in phonological theory (Selkirk 1981, 1982; McCarthy 1979; Lapointe and Feinstein 1982; Itô 1986, 1989; among others). This research has clearly shown that there is a direct relation between such phonological operations and the phonotactic constraints of a language, as expressed by well-formedness constraints on syllables. If cognitive phonology merely provides a syntax for epenthesis and deletion operations, one might expect any arbitrary rule, such as the insertion of a vowel between two vowels, or the deletion of a vowel between consonant clusters.

In our model, syllabification is an operation on the M-level buffer whereby segments are clustered into constituents based primarily on sonority (Vennemann 1972; Kiparsky 1979; Selkirk 1984), with additional rules reflecting language-specific restrictions. The standard notion of syllabification is a process that groups segments into tree structures composed of an onset, nucleus, and coda, where the latter two components form the rime. In our implementation there is no need to represent the rime explicitly, and we do not actually build tree structures (Wheeler & Touretzky 1990). Instead, each M-level segment is simply labeled as being in an onset, nucleus, or coda, as in the example below. Syllable boundaries are implicit in this representation.[6]

[6]There is one case where syllable boundaries are not implicit. If two consonants adjacent at M-level are marked as onsets, but are to be separated by an epenthetic vowel at P-level, one must look at the P-deriv insertion slot to detect the epenthetic nucleus. For example, in a language with only CV syllables, both consonants in the M-level sequence CCV would be marked as onsets, but they do not form an onset cluster; each belongs to a separate syllable, being realized as CVCV at P-level.

	M:	t	y	o	h	t	ũ	*"nine"*
onset:		+	+			+		
nucleus:				+			+	
coda:					+			

Following Itô (1986), and her notion of prosodic licensing, we explain epenthesis as an artifact of the syllabification process. When the segments of a consonant cluster aren't licensed by existing syllables, we insert a vowel to form a new syllable consistent with the prosodic constraints of the language. For example, in the derivation of "I will push it,", the final /k?/ sequence cannot form a legal coda, and so an /e/ is placed in the insertion slot between them. The first consonant is then marked as the onset of a new syllable, and the second is marked as the coda. The epenthesis actually takes effect at P-level, and so the epenthetic vowel is not explicitly represented below:

	M:	y	ʌ̃	k	h	r	e	k	?
onset:		+			+	+		+	
nucleus:			+				+		
coda:				+					+

An additional example is shown in Figure 3, where epenthesis breaks up a triconsonantal cluster in /ikks/ "I eat," producing the P-level representation /íkeks/. Notice that the stressed vowel /í/ is technically syllable-final since it is not followed by a coda. Therefore it will be subject to lengthening at P-F, with simultaneous application of voicing, resulting in the surface form [í:geks].

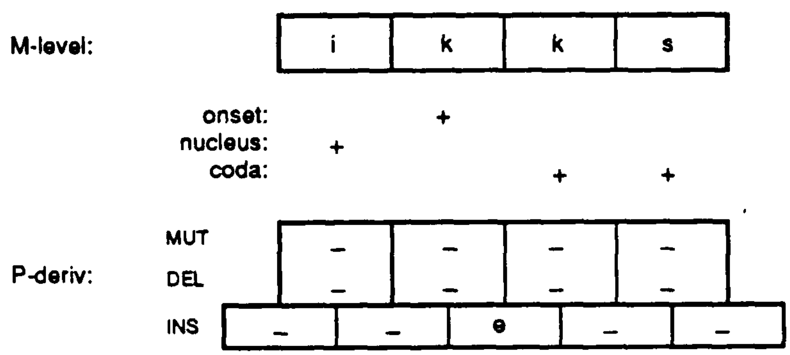

Figure 3: Insertion of an epenthetic vowel by the syllabifier.

Deletion is also explained in our model as a consequence of the need to form legal syllables. Recall that there is a deletion process in Mohawk which typically deletes the second of a sequence of two vowels. Adjacent vowels cannot both be marked as nuclei, as shown below in the syllabified representation for /hro-ahtũ/ "he has disappeared". Deletion occurs automatically in our M-P mapping when an M-level segment has not been marked as an onset, nucleus or coda by the syllabifier. This form will surface phonetically as [róhdũ] at F-level.

	M:	h	r	o	a	h	t	ũ	*"he has disappeared"*
onset:		+	+				+		
nucleus:				+				+	
coda:						+			

We now present our Mohawk stress assignment rule. Lakoff's version assigned stress to the penultimate P-level vowel. Instead, we stress the penultimate M-level nucleus.[7] Vowels that are subject to deletion will not have their NUCLEUS bit turned on, and therefore will be invisible to stress assignment. The notation M[nucleus] indicates that the rule is operating on the nucleus projection of M-level, i.e., looking only at segments which have the NUCLEUS bit turned on.

Stress assignment:	M[nucleus]:	[ ]	[ ]	#
		|		
	P:	[+stress]		

Returning to the derivation of /hro-ahtũ/, notice that it is the antepenultimate vowel of the underlying form that is stressed at the surface. Lakoff's analysis relied on an M-P vowel deletion applying prior to a P-level stress assignment rule. Since stress assignment is an M-P rule in our analysis, we need another, earlier level at which vowel deletion can take place. However, this need not be a derivational level like the M-P and P-F maps. Its function is accomplished by the independently-needed syllabifier. The /a/ which is to be deleted is made invisible to the stress assignment rule because the rule looks only at nuclei.

This entire section of the paper rests on the assumption that there is an effective procedure for syllabifying M-level sequences. We now turn to the specifics of this procedure.

6 The Syllabification Process

We have not yet settled on a universal syllabification algorithm, so our simulation uses a prototype syllabifier that has been tailored to work correctly for Mohawk. Since this paper is primarily about the *consequences* of adding syllabification to our model, the specific details of the syllabification algorithm are not essential here. The basic procedure for Mohawk is:

1. Turn on the NUCLEUS bit for the leftmost of every sequence of [+syllabic] elements.
2. Turn on the ONSET bits for the longest sequence of consonants, proceeding leftward from a nucleus, that forms a legal onset cluster.
3. In sequences of consonants not marked as onsets, turn on the CODA bits for the longest subsequence, starting from the rightmost element, that forms a legal coda cluster.
4. If an unsyllabified consonant remains, mark it as an onset, and insert an /e/ between it and the coda consonant to its right.

An intriguing alternative approach to syllabification has been suggested in recent work by Goldsmith and Larson (1990). Syllabification is determined by assigning numerical sonority values to localist connectionist units representing segments, and then applying a relaxation method with

[7] Actually we stress the penultimate syllable (Wheeler & Touretzky 1990). For the purposes of this paper, "nucleus" and "syllable" are equivalent.

lateral inhibition to derive sonority contours for syllables. Peaks in the derived sonority function correspond to syllable nuclei; troughs mark the beginning of syllable onsets.

While some future version of the Goldsmith and Larson architecture might be incorporated into our model, at present we cannot see how their approach offers a solution to the epenthesis and deletion processes discussed here, given the nature of their derived representations.

Our syllabification algorithm may appear sequential, but all syllables in the M-level buffer are processed simultaneously. The only sequential aspect is the leftward spreading of onset and coda bits within the limited bounds of well-formed clusters. Goldsmith and Larson also process entire words in parallel. Although they utilize a more homogeneous form of computation (namely, parallel relaxation), their algorithm still requires a series of updating cycles before settling into its final solution state.

7 Discussion

Two other Mohawk epenthesis processes are worth noting, although both are somewhat outside the scope of our model. First, there is a minimal word constraint, whereby verb roots must be at least bisyllabic to be acceptable. According to Mithun (personal communication), if a verb would otherwise have only one syllable, the vowel /i/ is added at the beginning to bear stress. In our analysis, the /i/ must be present in the M-level buffer in order to be a target of stress assignment, as in the example below:

M:	i + h r a + k + s	*"he eats"*
	|	*stress*
P:	í h r a k s	
	| |	*lengthening, falling tone, h-deletion*
F:	ì: r a k s	

Thus, our model locates epenthetic processes resulting from minimal word constraints at some point between the lexicon and the M-level buffer, an area we have not explored to date.

In a second epenthesis process that appears to be morphologically conditioned, the epenthetic vowel cannot appear in the M-level representation because it is not counted by the stress assignment rule. It is apparently an M-P rule that inserts /a/ between an incorporated noun stem and the following verb root if the noun stem ends in a consonant and the verb begins with one. At the moment we have no morphological component to our model, and consequently are unable to incorporate morphologically-conditioned rules. This does not seem to be an insurmountable problem.

Two Derivations Suffice

In summary, we have discussed how our model treats the following eleven processes of Mohawk phonology:

Morph.	epenthetic /i/ in monosyllabic roots
M-P	vowel deletion (by syllabifier)
M-P	epenthetic /e/ in CC# and CCC (by syllabifier)
M-P	epenthetic /a/ in noun incorporation (morphologically conditioned)
M-P	penultimate stress
P-F	palatalization
P-F	presonorant voicing
P-F	lengthening in stressed open syllables
P-F	stress to long vowel with falling tone and glottal stop deletion
P-F	stress to long vowel with falling tone and /h/ deletion before sonorant consonants
P-F	obstruent-sonorant /e/ epenthesis

8 Conclusions

Itô's (1986) notion of prosodic licensing dictates that each segment must be syllabically sanctioned. Individual languages have different strategies for dealing with stray or unlicensed segments. In Mohawk an epenthetic vowel breaks up illegal consonant clusters, while stray vowels delete. Preliminary research shows that epenthesis in Icelandic and Yawelmani can be handled by our syllabifier in the same way. We're currently investigating Lardil, an Australian language in which deletion is considerably more complex, requiring (in the generative analysis) several intermediate stages.

Our "many maps" model has been applied to processes in several other languages cited by Lakoff (vowel shortening in Slovak and Gidabal, Yawelmani vowel harmony, Icelandic umlaut), and also voicing assimilation in Russian. In each case two levels of derivation, with some non-derivational clustering machinery, have been sufficient. The syllabifier acts as an additional non-derivational mechanism that extends the power of our model without introducing additional levels of derivation. We speculate that "two levels of derivation" is a computational constraint met by the phonological components of all human languages.

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